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Reviewed Paper

Increasing process speed in the laser melting process of Ti6Al4V and the reduction of pores during hot isostatic pressing

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Abstract

Additive manufacturing of titanium alloys has gained intensive attraction from industry and academia. Moreover, for additively fabricated parts consisting of Ti6Al4V, hot isostatic pressing (HIP), is widely used as a post treatment in order to increase the relative density of the built parts. However, one aspect which has rarely been addressed so far, is the increase of process speed, accompanied by a reduced relative density in the as-built condition and a subsequent hot isostatic pressing process to achieve the desired dense material. The approach here is to use the standard process route as described, but intentionally increase the process speed and accept a certain value of porosity. The focal objective of this study is the identification of a parameter-set with the highest potential for an increase of process speed and subsequently reduce the internal defects during the hot isostatic pressing process to achieve completely dense components.

Introduction

Additive manufacturing (AM) processes are widely used in industry and represent a regular feature of the product development process [1]. There are different technologies (*i.a.*, selective laser melting of metals, selective laser sintering of polymers and fused deposition modelling of polymers), which are summarized under the term AM. All of them create a part by adding material rather than subtracting material as conventional machining [2, 3]. The huge possibilities of this technology, in case of design freedom for structural and functional parts, lead to a high demand for lightweight components in several industries (i.a. aerospace, medicine, automotive) [2]. Concerning SLM, it is a tool-free process in which the component is generated in a layer by layer fashion. Therefore, the components three dimensional geometry design is digitally sliced in several two dimensional layers, which are loaded in the machine. Thin powder layers, *e.g.,* 50µm, are deposited on a building plate one after another with a recoater and the two dimensional geometry is successively molten by the ytterbium laser. After solidification of the current layer, the building plate is lowered in z-direction, in exactly one layer height, and the recoater deposits the next powder layer such that the process restarts. Thereby nearly any complex geometry can be manufactured step by step [3, 4]. The unmolten material can be reused after a sieving process. Due to the high energy input, large thermal gradients and emerging residual stresses occur during solidification. Thus, each component requires support structures to avoid warping. [4, 5].

Nowadays, the highest cost driver is the SLM-processing time and the mechanical post-processing. On that account, SLM machine manufacturers develop enhancements to increase the efficiency of their machines. SLM machines are available with multi-laser optical systems to increase process speed and create fully dense components [6, 7]. Current machines as the single laser or the multi-laser machines can achieve building rates from $20cm^3/h$ up to $105cm^3/h$, by employing a laser power between 200W and 1kW [7]. With the help of multi-laser systems the building rate can be increased by the amount of lasers as a factor in building time reduction of a similar build job. These systems divide the 2D building area in separate scanning areas [3]. Another field of research addresses high power SLM, which means to increase the laser power up to, *e.g.*, 2kW and adjust the scanning strategy in order to generate components with a density of more than 99.5% [8, 9]. An established processing route for SLM components consisting of Ti6Al4V can be divided in five steps: the production process; a first heat treatment (stress-relief annealing, in which components stay on building plate); mechanical post-processing (cut components from building plate, and remove support structures); a second heat treatment (hot isostatic pressing to reduce internal defects); and a final mechanical post-processing of interfaces and functional surfaces (*i.a.,* milling or further machining) [3]. During hot isostatic pressing, which is a process where components are pretermitted high temperatures up to 1200°C and isostatic pressure around 1000bar, internal defects are closed and density increase up to 99,99%. The conditions during the HIP process lead to localized plastic deformation and solid-state diffusions take place [6].

Within the current work, the focus is on the powder-bed based selective laser melting (SLM) of metals, respectively titanium alloy Ti6Al4V. Especially, in the aerospace industry, Ti6Al4V components fabricated by SLM, offer high potential due to its severe weight savings potential based on the low density 4,43 g/cm³ of Ti6Al4V.

Therefore, the approach here is to decouple the increase of process speed from the hardware of a machine, but develop an adapted process idea. The aim is to use the default and known process route for Ti6Al4V parts, identify a high speed SLM parameter set and get the same density as before through the use of the HIP process.

The approach is to optimize the first step in the described process route by optimizing the building parameters and accept a slightly higher porosity due to an increased process speed. During the HIP process internal defects are eliminated. Regardless of whether the specimens have a density value around 99,9% or around 97%. The results show, that the density at the end of the process route can be similar, the only difference is the building time of the specimen. The building time can be reduced up to 50%, while still getting dense products. Due to the use of a default and known process route with little changes in the subject, the procedure described in here is transferrable to several other systems as well.

Experimental Details

The material used in this work was gas atomized titanium alloy Ti6Al4V powder. The chemical composition of the powder was determined by different testing methods, as can be seen in Table 1.

Table 1 – Chemical composition measured of the used Ti6Al4V powder.

Chemistry	Al	C	Fe	H	N	O	Ti	Va	Other
Test Method	ICP	Leco	ICP-MS	Leco	Leco	Leco	Diff	ICP	ICP-MS
Result	6.36	0.01	0.04	0.0044	0.02	0.12	Balance	3.98	0.16

The size of the atomized particles were in the range from d(0.1): 19.8µm – d(0.9): 77.15µm with an average particle size of d(0.5): 41.99µm. As shown in Figure 1 a), the particle size distribution possessed a Gaussian function. In addition, the particle morphology can be described as spherical in shape (Figure 1 b)). The particle morphology was analyzed with a scanning electron microscope

(SEM). A spherical particle morphology was required for a sufficient powder flowability and thus a homogenous powder layer deposition.

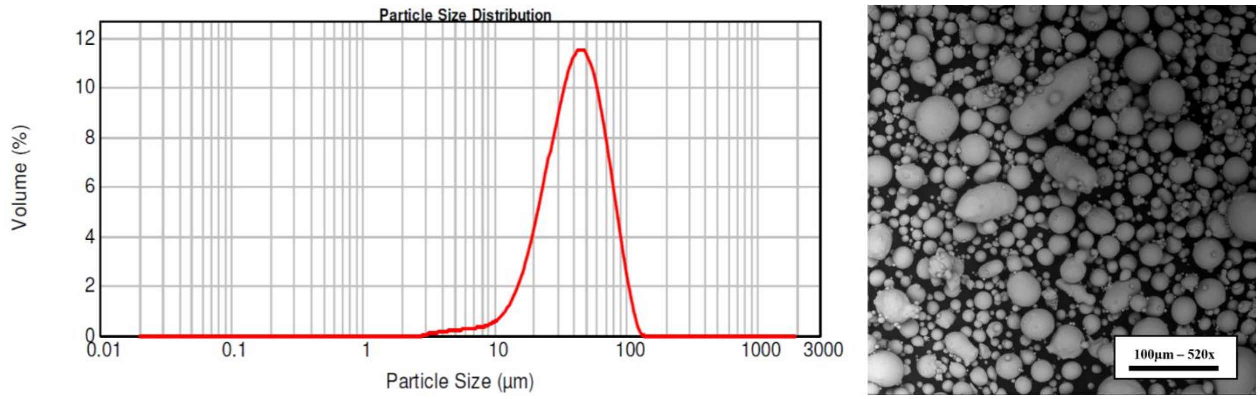


Figure 1 – Particle size distribution and particle morphology

For specimen fabrication, a SLM 280^{HL} (SLM Solutions Group AG, Lübeck, Germany) was applied. The system was supplied with a 400W Ytterbium fiber Laser. The beam focus diameter possessed a size of 70µm and a Gaussian power distribution. Table 2 reveals the reference SLM parameter-set, which was basis for the parameter variation. Cylindrical specimens with a height and a diameter of 10mm were additively manufactured. Overall, the design of experiment included 20 different parameter-sets and 60 specimens in total by the variation of laser power (275W up to 385W), scanning speed (760 mm/s up to 2500 mm/s) and hatch distance (0,12 mm up to ,018 mm). The resulting volume energy density varied from 26,7 J/mm³ to 60,31 J/mm³. The parameter study based on a previous investigation of the authors. All specimens were built with a layer thickness of 50µm and a building-platform temperature at 200°C. In order to reduce internal defects, a HIP process was performed at 920°C/1000 bar on one half of the specimen.

Table 2 – Reference parameter for specimen production

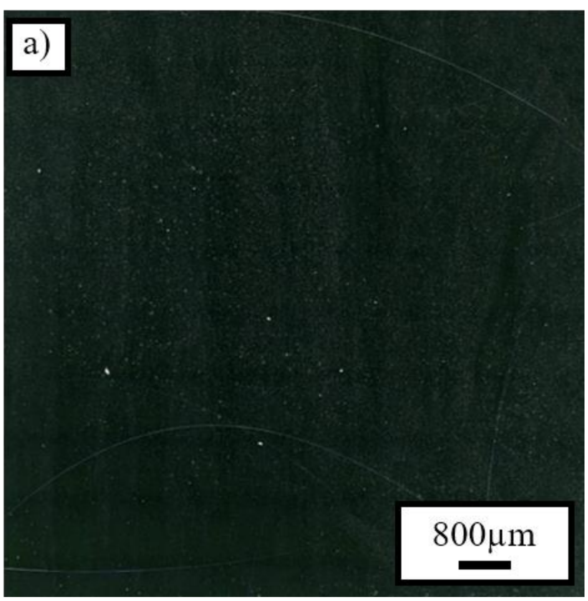
Parameter	Laser power [W]	Scanning speed [mm/s]	Hatch distance [mm]	Volume energy density [J/mm³]
Reference Hatch	275	760	0,12	60,3

For dark field optical images, the samples were mechanical grinded down to 6µm grit size and then vibro-polished using a colloidal silica suspension with a pH-value of 10 and a particle size of 0.06µm. The metallographic cross sections were subsequently analyzed by the software Clemex Vision Lite (Longueuil, Canada) with regard to grayscale differentiation in order to quantify the prevailing relative density. Furthermore, the specimen were etched for 20 sec. in etchant according to Kroll. The building time calculation was done with the Software Magics from Materialise.

Results and Discussion

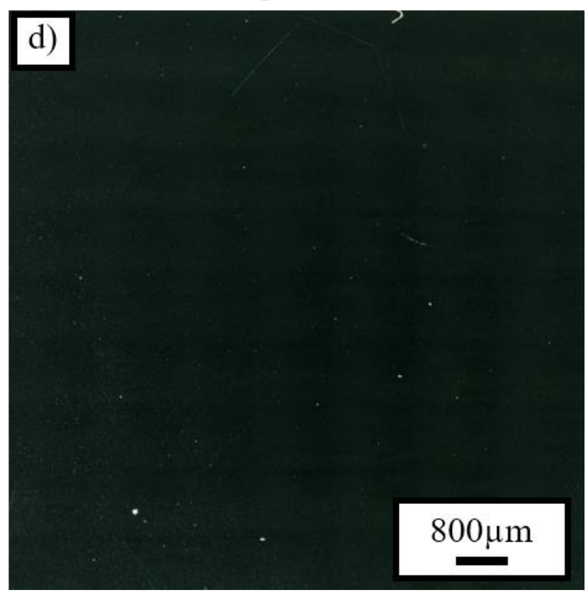
Figure 2 depicts representative dark field micrographs of the samples' cross sections (x-z-plane); three specimens in the as-built condition and similar specimens after the HIP process. The density in as-built condition processed with the standard parameter-set is determined at 99,97% and at 99,99% after the HIP process. The samples fabricated with 29,17 J/mm³ and a calculated processing time reduction of 51% possess a relative density in the as-built condition of 99,21% and of 99,95% after the HIP process. The samples manufactured with 30,85 J/mm³ and a calculated processing time reduction of 49% has a density in as-built condition of 99,14% and of 99,97% after HIP process.

As build



60,31 J/mm³ - Reference

HIP processed



60,31 J/mm³ - Reference

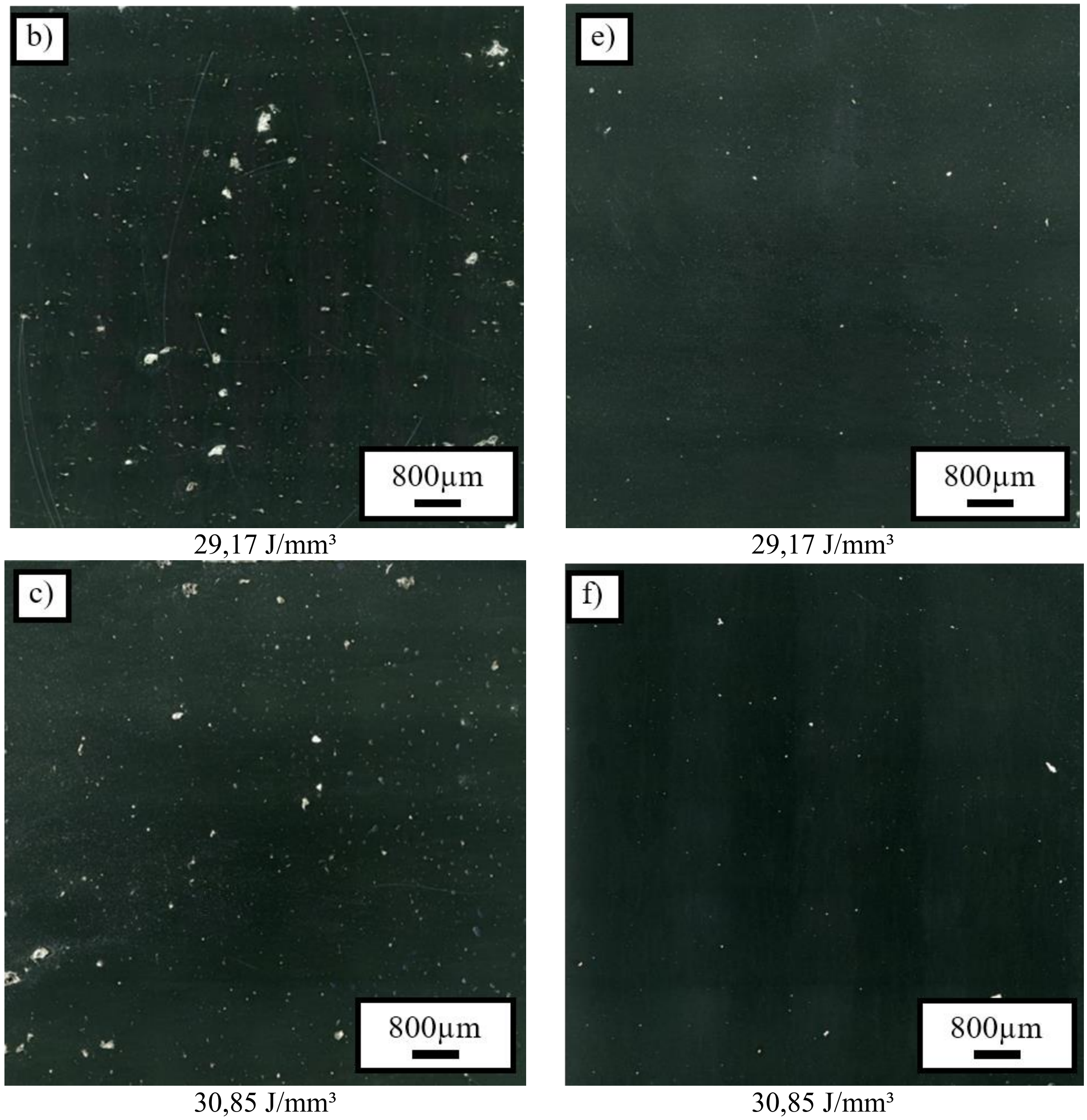


Figure 2 - Dark field optical images displaying cross sections of the SLM processed specimens in the as-built condition (a)-(c) as well as the HIP-condition (d)-(f).

In Figure 3, the effect of the HIP process on the porosity and the resulting time reduction is shown. It can be observed that by employing a subsequent HIP process the density is significantly higher than before the post-treatment. Sample 1 (S1) represents the reference parameter-set with a slightly increase of laser-power. The samples S5 and S8 are built with 29,17 J/mm³ and 30,85 J/mm³ and can be compared to the cross section images shown above. The highest density increase was measured for the condition S10, in which the porosity decreases from over 6% to less than 0.01%, while achieving a time reduction of approximately 52%. In addition, an economic approval was carried out. Based on three different buildjobs with different building heights, space utilization and volume components, the potential was examined on economic aspects.

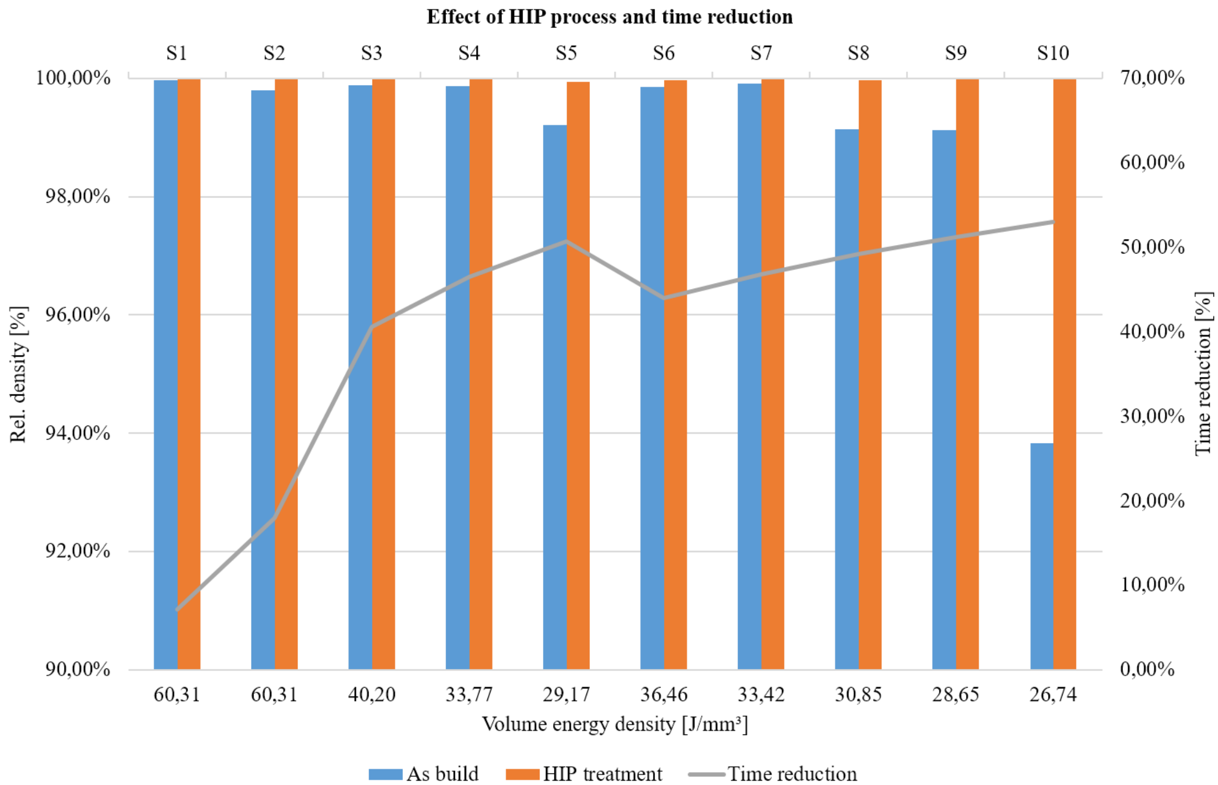


Figure 3 – Optical density analysis of cross section images (x-z-plane)

In Figure 4, optical images are displayed revealing six representative microstructures of the SLM-processed and HIPed specimens after etching. As Leuders et al. showed in previous investigations [10,11], a lamellar α-titanium phase can be detected in this images as well. Since the β-transus temperature of Ti6Al4V is at 995°C, there is no β-titanium expected.

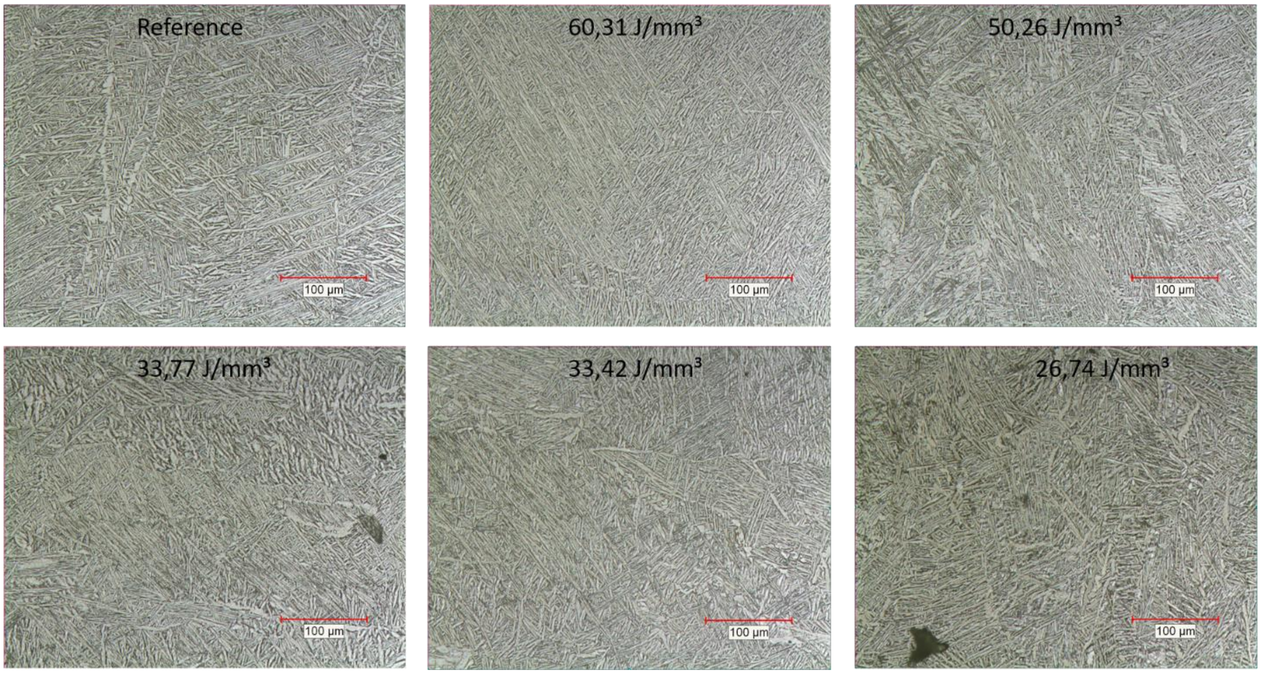


Figure 4 – Microstructure of Ti6Al4V specimens with different parameter sets

In consequence, the similarity of the microstructure leads to the assumption that the chosen volume energy density does not lead to any microstructural changes after HIP process. In combination with the density measurements, it can be presumed that it is feasible to fabricate components with similar properties in severely reduced SLM-processing time (time reduction between 13% and 48% in Figure 43) by conducting the investigated procedure.

Conclusions

The presented results demonstrate the potential of the high-speed SLM strategy. A marginal process route modification can obviously lead to a severe reduction of 50% in SLM-processing time.

Based on the conducted investigations, the current findings can be summarized as follows:

1. The HIP process is able to reduce porosity from up to 6% to 0.01%.
2. Processing time can be reduced up to 50% on optimal conditions for Ti6Al4V components using the described process route.
3. By varying the parameter sets and the knowledge gained with regard to the density, it is now possible to adjust the density in a targeted manner.

4. No negative modifications in the microstructure of the specimens after HIP process caused by the build time reduction and the accompanying build rate increase.

The described approach has to be validated with experiments on the mechanical properties of specimen produced with the optimized parameters and the adapted process route. Moreover, the approach has to be transferred to other machines.

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References

[1] German Association of Engineering VDI (deutsch: Verein deutscher Ingenieure): VDI 3405 – Additive Manufacturing Processes – Basics, Definitions, Processes; 2014

[2] Wohlers, T.: "Wohlers Report 2015 – 3D Printing and Additive Manufacturing State of the Industry. Annual Worldwide Pogress Report, 2015

[3] Gebhardt, A.: „Generative Fertigungsverfahren – Additive Manufacturing und 3D Drucken für Prototyoing – Tooling – Produktion", Carl Hanser Verlag, Munich, 2013

[4] Gibson, I.; Rosen, D.; Stucker, B.: „Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping and Direct Manufacturing", Springer Verlag, New York, 2015

[5] German Association of Engineering VDI (deutsch: Verein deutscher Ingenieure): VDI 3405 Blatt 2 – Additive Manufacturing Processes – Qualification, quality assurance and post processing; 2013

[6] Yang, L.; Hsu, K.; Baughman, B.; Godfrey, D.; Medina, F.; Menon, M.; Wiener, S.: "Additive Manufacturing of Metals: The Technology, Materials, Design and Production", Springer Verlag, Cham (Schwitzerland), 2017

[7] SLM Solutions: Product Datasheet SLM500HL, https://slm-solutions.de/sites/default/files/downloads/w_slm500_de.pdf, 2016, Accessed 26 June 2017

[8] Schniedenharn, M.; Liu, Q.: “Aufbauratensteigerung mittels High Power Selective Laser Melting für den Werkstoff Ti6Al4V”, Fraunhofer ILT, Rapid.Tech, 2016

[9] Bremen, S.; Meiners, W.; Wissenbach, K.; Poprawe, R.: “Correlation of the High Power SLM Process with Resulting Material Properties for IN718”, BHM Berg- und Hüttenmännische Monatshefte, 2017

[10] Leuders, S.; Lieneke, T.; Lammers, S.; Tröster, T.; Niendorf, T.: “On the fatigue properties of metals manufactured by selective laser melting – the role of ductility“, JMater Res, 29 (2014), pp. 1911-1919

[11] Leuders, S.; Vollmer, M.; Brenne, F.; Tröster, T.; Niendorf, T.: „Fatigue strength prediction for titanium alloy Ti6Al4V manufactured by selective laser melting“ Metall Mater Trans A (2015)